

Technical Note

Advances in a 300 Hz thermoacoustic cooler system working within liquid nitrogen temperature range

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ABSTRACT

With the combined advantages of high reliability, compact size and low electromagnetic interference, a high frequency operating thermoacoustic cooler system, i.e. a pulse tube cooler driven by a thermoacoustic heat engine, is quite promising for space applications. This article introduced a high frequency standing-wave thermoacoustic heat engine-driven pulse tube cooler system working around 300 Hz with axial length being 1.2 m. To improve the thermal efficiency of such system, an optimization has been carried out, both analytically and experimentally, by observing the influence of the dimensions of the stack, the hot buffer length and the acoustic pressure amplifier tube length. So far, a no-load temperature of 68.3 K has been obtained with 4.0 MPa helium and 750 W heating power. With 500 W heating power, a no-load temperature of 76.9 K and 0.2 W cooling power at 80 K have been achieved. Compared with former reports, the performance has been improved.

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1. Introduction

Small scale cryocoolers play important role in space applications. As thermoacoustic cooler system possesses virtues such as no moving components and high reliability [1,2], a high frequency system with compact size could be a very promising alternative for future space missions. In 1996, Godshalk et al. made the first attempt and obtained a lowest cold-head temperature of 147 K at 350 Hz [3]. In 2006, we have obtained a lowest temperature of 95 K on a 300 Hz thermoacoustic cooler system [4]. After that, some modifications of the system have been done in terms of the resonator of the standing-wave engine and the phase shifter of the pulse tube cooler, and finally a no-load temperature of 69.5 K has been achieved but with a heating power of 1.76 kW [5]. Most recently, we have much improved the stack manufacturing quality and obtained a lowest temperature of 68 K and a cooling power of 1.16 W at 80 K with engine heating power being 1 kW [6]. But the system could hardly provide cooling power at 80 K with heating power at around 500 W.

Aiming at several hundreds of mW cooling power at 80 K with minimum engine heating power requirement, this paper further optimizes the system both analytically and experimentally. To date, a no-load cold-head temperature of 76.9 K and a cooling power of 0.2 W at 80 K have been obtained with 500 W heating power. The following section introduced the experimental system. Systematical analysis and optimization methodology are given in

detail in Section 3, followed by experimental results in Section 4. Finally, some conclusions and discussions are made.

2. Experimental setup

The experimental setup of the 300 Hz high frequency thermoacoustic cooler system is shown in Fig. 1, which consists of a high frequency standing-wave thermoacoustic engine (SWTE), an acoustic pressure amplifier tube (APAT) and a pulse tube cooler (PTC). The SWTE consists of a hot buffer, a heating block, a stack, an ambient heat exchanger (HX) and a resonator. The detailed dimensions are listed in Table 1. To ensure relatively high efficiency operation of the engine, the stack is made from piled and carefully-aligned stainless steel plates with elaborate narrow channels on it. The PTC mainly includes an ambient heat exchanger, a regenerator, a cold head, a pulse tube, an ambient end and an inductance tube. Details of the PTC dimensions are listed in Table 2. The SWTE and the PTC are coupled through an APAT whose inner diameter is 4.3 mm and length is variable.

For the SWTE, electric cartridge heaters are imbedded in the heating block for heat input. The hot parts of the system are insulated from the environment with several layers of ceramic fiber blanket. K-type sheathed thermocouple T_h is inserted in the heating block to measure the temperature of the solid therein. For the PTC, a calibrated platinum film resistance thermometer T_c is used to measure the temperature at the cold head of the PTC. Piezoelectric pressure sensors P_1 and P_2 are mounted at the two ends of the APAT to measure the pressure oscillation therein. For all the experiments here, helium gas is used.

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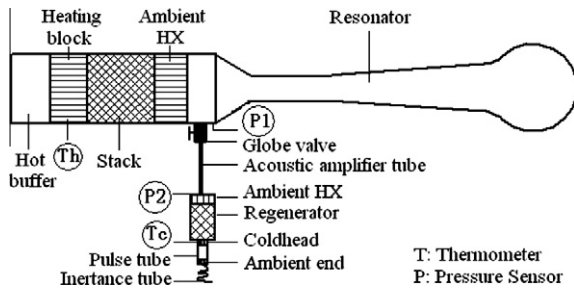


Fig. 1. Schematic drawing of a 300 Hz high frequency thermoacoustic cooler system.

Table 1

Details of the high frequency standing-wave thermoacoustic engine.

Components	Dimensions
Hot buffer	i.d. 50 mm, length to be optimized
Stack	i.d. 50 mm, length and channel spacing to be optimized
Resonator	Mainly 450-mm cylindrical tube + 400-mm tapered tube (29- to 71.8-mm i.d.) + 151-mm i.d. spherical vessel

Table 2

Details of the pulse tube cooler.

Components	Dimensions
Regenerator	i.d. 10 mm, length 30 mm, filled with 600 mesh stainless steel screen
Pulse tube	i.d. 6 mm, length 40 mm
Inertance tube	i.d. 2 mm, length 300 mm + i.d. 4.3 mm, length 1100 mm

3. Optimization scheme

The SWTE could be deemed as a heat-driven thermal compressor, which produces acoustic power to drive the PTC to obtain cryogenic temperature. Roughly speaking, with a larger acoustic power produced, a lower cold-head temperature and larger cooling power could be achieved by the PTC. According to the linear thermoacoustic theory [7], the derivative of acoustic power per unit length in the stack is described as

$$\frac{dE_2}{dx} \approx -\frac{r_\mu}{2}|U_1|^2 - \frac{1}{2r_\kappa}|\bar{p}_1|^2 + \frac{1}{2}\frac{1}{T_m}\frac{dT_m}{dx}\text{Im}[\bar{p}_1 U_1]\text{Im}[-f_k] \quad (1)$$

where T_m is mean temperature, $\bar{p}_1$ and U_1 are dynamic pressure and volume flow rate, respectively, r_μ and r_κ are viscous and thermal relaxation resistance per unit length, respectively, and f_k is thermal function. The first and second items at right hand side of Eq. (1) represent the acoustic power loss while the last item represents the acoustic power production therein. Obviously, the increase of temperature gradient across the stack and the increase of $\text{Im}[\bar{p}_1 U_1]\text{Im}[-f_k]$ both lead to larger acoustic power production. And the former could be realized by optimizing the lengths of the hot buffer and stack without increasing the heating power and the latter could be achieved by optimizing the dimension of the stack according to specific operating parameters.

Meanwhile, properly using APAT is critical to obtaining good efficiency of the whole system. As indicated in Fig. 2, with mean pressure of 4.0 MPa and the given impedance of PTC whose cold-head temperature is fixed at 80 K, an optimum APAT could lead to a pressure amplitude amplification ratio as high as 5, which could greatly increase the acoustic power into the PTC comparing to that without APAT if we do not consider the output acoustic

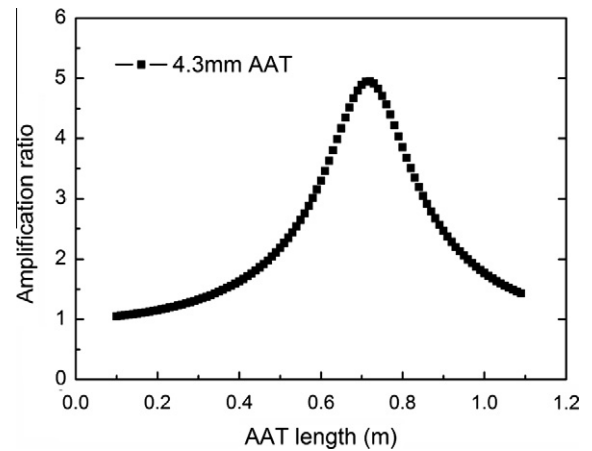


Fig. 2. Pressure amplitude amplification ratio of APAT vs. APAT length.

power capability of the thermoacoustic engine. However, it is due to this engine power output capability limitation, the practical length of the APAT used in the experiments cannot exceed 50 cm in Refs. [5,6], and a longer APAT may lead to either the occurrence of harmonic modes or even the failure of spontaneous oscillation. Another factor that should be considered is that, by using APAT, the pressure wave amplitude inside the engine is reduced. Although the amplification ratio is increased, excessively long APAT may lead to a decreased pressure wave amplitude at the inlet of the PTC compared with that using a shorter APAT. The determination of the optimum length of the APAT could only be done based on a system-level simulation and through experiments.

In fact, a system-level calculation based on the linear thermoacoustic theory and our simulation methodology [8] has been conducted to help optimizing the dimensions of hot buffer, stack and acoustic pressure amplifier tube. The following gives a typical example of the calculated influence of hot buffer length on the system performance. Dimension of the PTC is kept unchanged in the calculations. With 29 cm APAT, 3.92 MPa helium and a heating power of 750 W, Figs. 3 and 4 show the calculated distributions of volume flow rate amplitude and acoustic work in the coupled system, respectively. As observed in these two figures, the volume flow rate provided by the engine at where the engine and the APAT meet is increased by using a longer hot buffer length. Meanwhile,

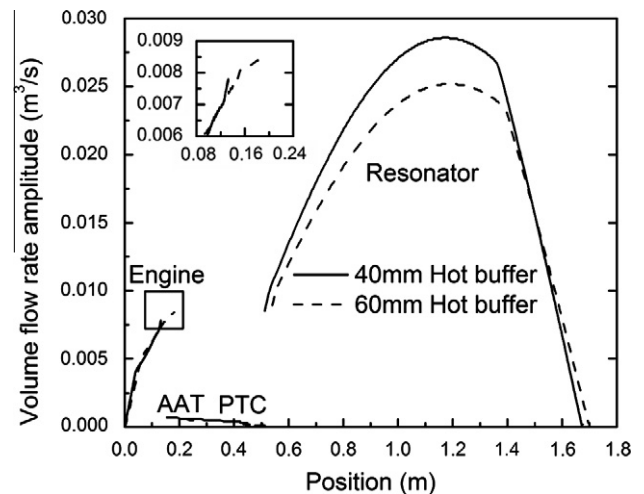


Fig. 3. Calculated distribution of volume flow rate amplitude in the thermoacoustic cooler system.

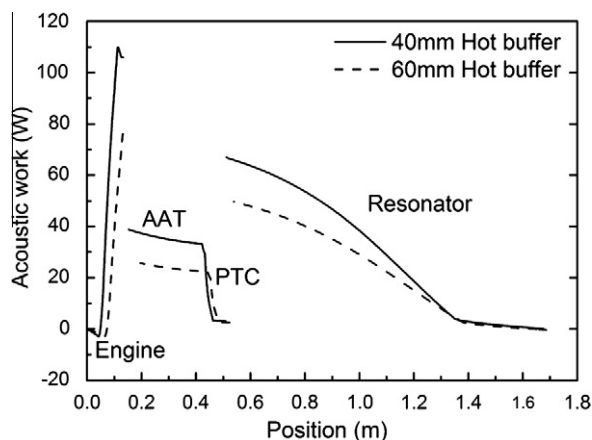


Fig. 4. Calculated distribution of acoustic work in the thermoacoustic cooler system.

Table 3

Details of the optimized results (diameter $\times$ length, mm).

Hot buffer	Heating block	Stack	Ambient HX	AAT
$\Phi 50 \times 30$	$\Phi 50 \times 20$	$\Phi 50 \times 80$	$\Phi 50 \times 15$	$\Phi 4.3 \times 580$

Table 4

Detailed comparison between this work and Ref. [6].

	Heating power (W)	Pressure ratio at P_1	T_c (K)
Ref. [6]	750	1.198	77
This work	500	1.198	76.9
Ref. [6]	1000	1.223	68
This work	750	1.219	68.3

the pressure wave amplitude at the inlet of the PTC is decreased which leads to a reduced acoustic power and worse PTC performance. However, the afore-mentioned increase of volume flow rate makes it possible to use a longer APAT to make up for the reduced acoustic power as evidenced in Table 4 of Ref. [9].

It should be emphasized that due to many non-linear factors inside these systems, the linear model cannot give very accurate results. In most cases, we still need experiments to verify and improve the system performance. In this way, the following gives relatively optimized results with dimensions of the SWTE and APAT listed in Table 3.

4. Experimental results

With the optimized dimensions of the coupled system, experiments have been carried out in terms of the no-load cold-head temperature and cooling power. To date, a no-load temperature of 68.3 K has been obtained with 4.0 MPa helium and 750 W heating power. With heating power reduced to 500 W, a no-load temperature of 76.9 K was obtained at a working frequency of 283 Hz. The typical temperature curve is shown in Fig. 5. It can be seen that when the temperature of the heating block rises to 453 °C, the spontaneous oscillation of the system starts, which leads to the decrease of the cold-head temperature of the PTC. After a time period of about 120 min, the system reaches a stable oscillation status. The net cooling power as a function of cold-head temperature is present in Fig. 6. For the operating condition given above with 500 W heating power, the net cooling power at 80 K is 0.2 W, and reaches up to 2.77 W at 120 K. A detailed comparison between

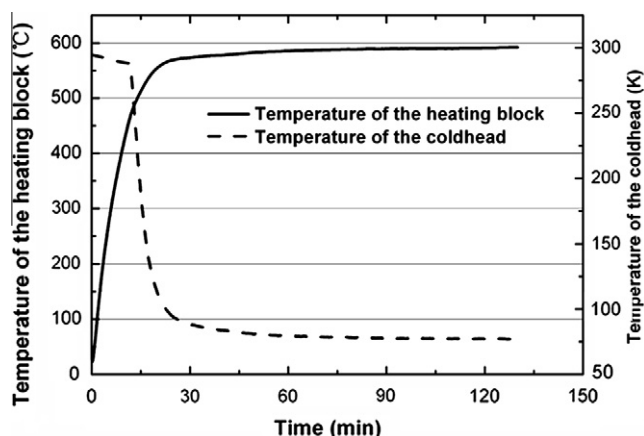


Fig. 5. Typical temperature curve of the system.

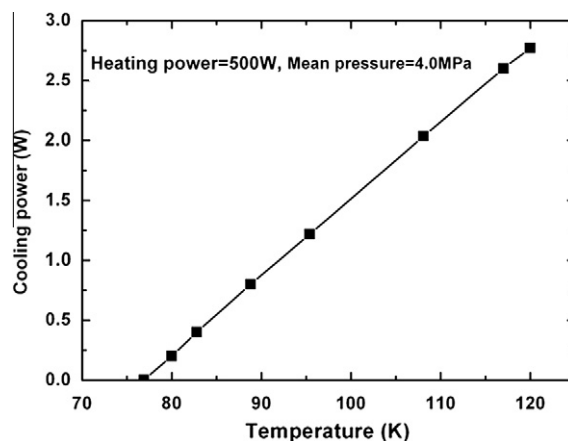


Fig. 6. Net cooling power of the PTC.

the experimental results of this work and Ref. [6] is given in Table 4. It indicates that with the optimization, for almost the same inlet pressure ratio and no-load cold-head temperature of the PTC, the required heating power decreases by 250 W in comparison with that of Ref. [6], which demonstrates improvement of thermal efficiency.

5. Conclusions and discussions

We have optimized and built a 300 Hz thermoacoustic cooler system, whose thermal efficiency is improved. A lowest temperature of 68.3 K has been obtained with 4.0 MPa helium and 750 W heating power. A no-load cold-head temperature of 76.9 K and net cooling power of 0.2 W at 80 K have been achieved with heating power of 500 W when operated at 283 Hz. These results show the capability of such a high frequency system and the potential for future space applications.

On the other hand, recent basic measurements show that thermal loss including radiation loss of the hot parts of the SWTE and heat conduction through the stack account for about 30% of the total heating power when the system reaches the stable state. A reduction of the loss would help to further improve the system performance. Meanwhile, other experiments in our lab also indicate that the cold end heat exchanger design is also important, which may be optimized to provide more cooling power at 80 K. A more accurate model would also help to optimize the system.

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